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IGNITION CHARACTERISTICS OF A TWO-COMPONENT CONDENSED FUEL IN A STAGNATION-POINT FLOW

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Two-component condensed fuel ignition behavior is observed in a hot stagnation-point air flow. Fuels utilized in this study are mixtures composed of hexane and solid paraffin with high and low volatilities. At time zero, the mixed fuel is exposed to a hot air stream directed downward onto the fuel surface at room temperature. When the external air flow velocity increases at a fixed flow temperature (1083 K), the ignition time reaches a minimum point, and then it increases again until it goes to infinity for a certain critical flow velocity. This ignitable limit is based on a critical Damköhler number for ignition. The variation of the ignitable limit with fuel composition under fixed air flow conditions, displays a characteristic curve. As the hexane percentage increases, the critical velocity reaches a maximum around 40 wt% and a minimum around 50 wt%. A supporting ignition time tendency is also obtained. Finally, a qualitative discussion of this type of ignition behavior for binary fuel mixtures is given. The phenomenon described here is readily apparent when the difference of the volatilities of the component fuels is quite large.

1. Introduction

The combustion characteristics of multi-component fuels, including water-oil emulsions, have been studied in order to improve efficiency and reduce NO_x emissions and soot formation in engines. Further field research on these problems is necessary since most fuels used in practical combustors are not completely refined, and various methods must be developed for the fire protection of the residual sludge or bilge oil, depending on the type of oil. The important feature of multicomponent fuels (or water-oil emulsions) is that they are mixtures of fuels with different volatilities. From this point of view, droplet vaporization or combustion of the fuel mixtures has been treated theoretically[1-5] and experimentally.[6-8] Reviews of such findings have been conducted by Dryer[9] and Law.[10] Most investigators, however, have focused their attention on the disruptive atomization and burning of the droplet; consequently studies on the ignition phenomena of a fuel blend are rare.

If the chemical reaction time of gasified fuel and atmospheric oxygen is quite short, the ignition time is nearly equal to the gasification time. Even if the reaction time increases, ignition/non-ignition depends on the gas-phase condition attained by heating. The gas-phase condition is formed in a very complicated manner; the gasification process is governed by the equilibrium equation for the gas-liquid interface, which depends on the initial composition of the fuel and the surface temperature. Since in a multicomponent condensed fuel, it is mainly the more volatile component that evaporates during heating, ignition is basically controlled by the vaporization of this component. However, the complete process is not so simple. For instance, although fuel containing a high percentage of volatile matter may vaporize rapidly, the gasified fuel temperature may not be high because the gasification temperature is lower near the boiling point. This being the case, if the gasification process or the mixing region of gasified fuel and oxidant possesses certain mixed fuel characteristics, ignition may occur in a complex manner. To understand the phenomena, a steady (or quasi-steady) gasification field and long ignition time behavior (obtained by extending the reaction time) are needed. (It is difficult to lengthen ignition time by slow vaporization because a long gasification period causes the gasified fuel to disperse, precluding ignition.)

The ignition source adopted here is a hot stag-

nation point flow stimulus, which can be treated as a one-dimensional system and is convenient for controlling the mass transfer field with changes in the approaching flow velocity. Longer reaction times can be obtained if the flow velocity is increased causing a decrease in the Damköhler number.[11] Since the steady (or quasi-steady) gas-phase mixing layer is established prior to ignition,[12] it facilitates the analysis of the ignition characteristics. Under this experimental condition, characteristic phenomena are found for the ignition time or ignition limit variation with the fuel composition, and, additionally, the phenomenological reasoning is demonstrated.

2. Experimental Method

The experimental technique is essentially the same as that employed for ignition of a reactive solid[13] and plastic materials[12] in a hot stagnation-point flow. As seen in Fig. 1, the hot air flow issues from a 20-mm diameter nozzle and impinges on the fuel surface. The distance between the nozzle outlet and the fuel surface is 14 mm. The dry air is heated by an electric furnace and the air flow temperature is kept constant (1083 K) at the nozzle outlet. Ignition times and ignitable limits are measured by allowing the nozzle outlet flow velocity (U_e) to change from 80 to 280 cm/sec. Ignition is detected by an infrared-sensitive detector aimed at the stagnation region and the distinct increase of infrared emission generated at ignition is recorded.

Mixtures of n-hexane and solid paraffin (melting point 324 K) are chosen as miscible fuels. In order to note specimen surface temperature changes in the fuel composition, fuels whose boiling points are as different as possible are selected. (This combination can be considered to be a model, for ex-
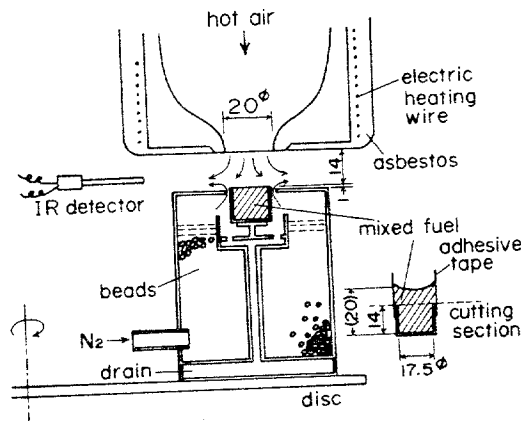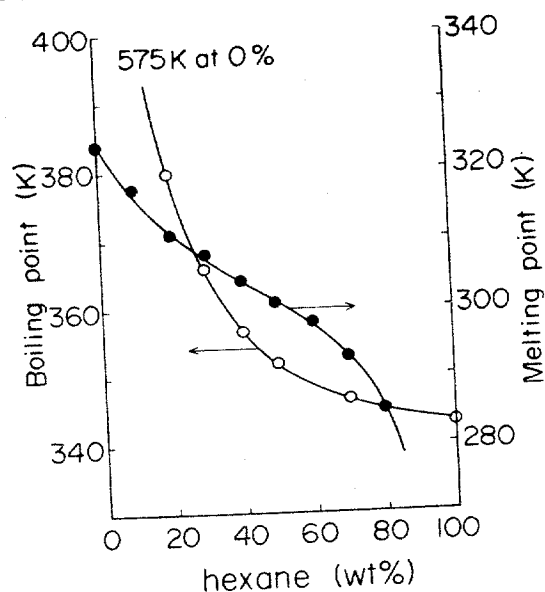
FIG. 2. Melting and boiling points of hexane and solid paraffin mixture.

ample, of crude oil.) Measured boiling and melting points of the mixtures are shown in Fig. 2. By adding n-hexane at room temperature to molten paraffin at about 330 K and cooling it, mixed gel type fuels with optional percentages can easily be obtained. When the molten fuel is poured into a cup of 17.5 mm diameter and 14 mm depth, there is a possibility that a small amount of n-hexane may vaporize near the surface during cooling. As illustrated in Fig. 1, the molten fuel is poured over a brass cup rim surrounded by adhesive tape and the upper part of the fuel is cut at the cup rim after solidification. Since the cutting is done immediately prior to the experiment, the fuel surface is always fresh and no concentration distribution exists near the surface. The fuel cup at room temperature is
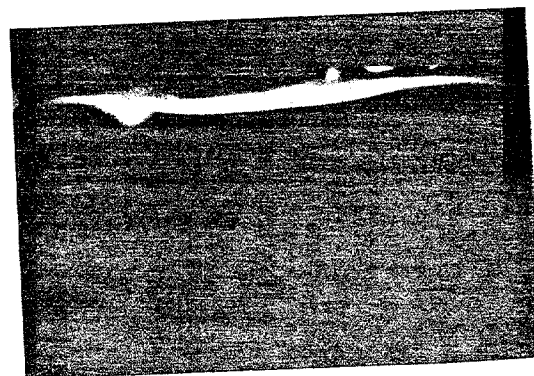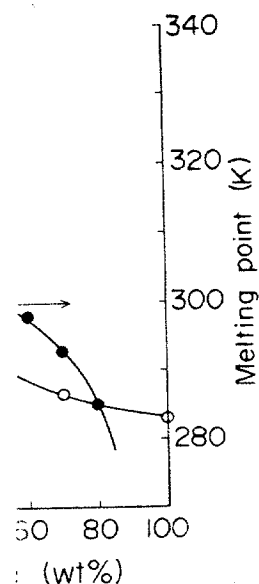
FIG. 1. Schematic diagram of experimental apparatus.

FIG. 3. Direct photograph of diffusion flame established after ignition.

340

320

300

280

Melting point (K)

→
●
●
○
●
○

50 80 100

(wt%)

ng points of hexane and

ared boiling and melting
shown in Fig. 2. By add-
perature to molten par-
oling it, mixed gel type
itages can easily be ob-
fuel is poured into a cup
14 mm depth, there is a
ount of n-hexane may va-
during cooling. As illus-
en fuel is poured over a
by adhesive tape and the
cut at the cup rim after
tting is done immediately
the fuel surface is always
n distribution exists near
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moved promptly just below the nozzle by turning
the fuel cup disc and the fuel surface is exposed to
a controlled hot air flow. A high speed camera con-
firms that ignition occurs near the fuel surface on
the center axis and that the reaction zone spreads
parallel to the fuel surface. The established diffu-
sion flame is shown in Fig. 3. Ignition times are
obtained from the time recorded from the position-
ing of the fuel cup to the increase in IR emission.
The fuel cup is surrounded by a nitrogen flow which
cools it and inhibits gas-phase reactions outside the
cup. All experiments are made at atmospheric pres-
sure.

3. Experimental Results and Discussion

3.1 *Variation with Flow Velocity*

Since the stagnation-point heat flux increases as
the nozzle outlet flow velocity increases at a fixed
flow temperature, both the condensed fuel gasifi-
cation and the ignition time should decrease with
flow velocity. The stagnation-point flow (or counter-
flow) system, however, forms a typical stretched-
flow field and therefore ignition with a small
Damköhler number can be achieved. The stretched-
flow causes the ignition time to increase in the larger
flow velocity region because the gas-phase reaction
time of fuel and oxygen is longer in this flow field.[11]
Therefore, the minimum ignition time results when
the flow velocity is changed. Such ignition time be-
havior was observed for plastic materials in a pre-
vious experiment,[12] and the same tendency appears
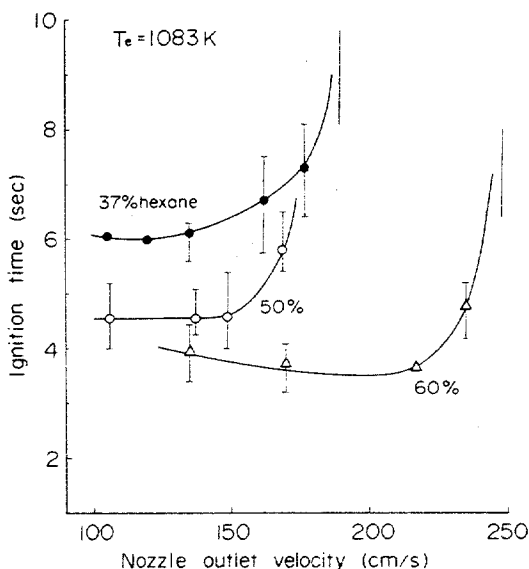for the present fuel, as seen in Fig. 4.

Figure 4 does not show distinct decreases in the
low velocity region prior to the minimum (termed
the pyrolysis or vaporization control region in pre-
vious experiments for plastic materials[12]), but the
ignition time increases in the high velocity region
even if the stagnation-point heat flux becomes large
relative to the square root of the velocity. The rea-
son for this is that although gasification occurs
quickly, the subsequent gas-phase reaction pro-
ceeds slowly in this stretched-flow field. Therefore,
the higher velocity area was designated as the re-
action control region.[12]

When the flow velocity is increased further, a
critical velocity is reached that prevents ignition.
Ignitable limits are illustrated in Fig. 4. Note the
unusual order of the ignitable limits: the critical ve-
locities of 37 wt% and 50 wt% the hexane mixed
fuel are reversed. The reason for this is given be-
low.

3.2 *Ignitable Limit*

To thoroughly investigate the reason why a mixed
fuel containing a large amount of high volatile fuel
(hexane) readily attains the ignitable limit, critical
velocities for fuels of various concentration were
measured. The ignitable limit curve is illustrated in
Fig. 5. Five hundred ignition tests were conducted
to confirm characteristic changes reported here.
Common sense dictates that the critical velocity will
be higher as the concentration of hexane increases:
Fig. 5 gives the maximum point around 40 wt%
and the minimum point around 50 wt% hexane.

Figure 6 shows the variation of ignition time with
the hexane percentage at constant external flow ve-
locities U_e = 135 and 165 cm/sec. It follows that
ignition times are obtained by traversing the line
which cuts across the limit curve of Fig. 5 once for
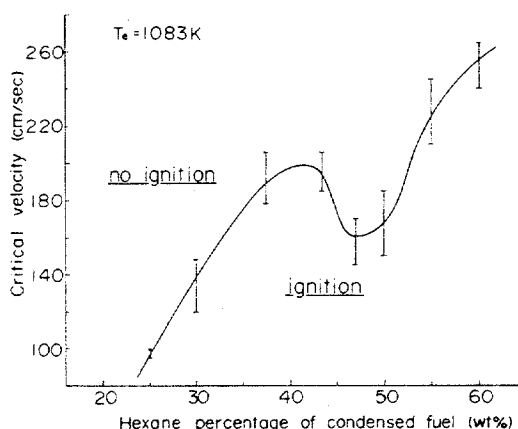U_e = 135 cm/sec and three times for 165 cm/sec.

FIG. 4. Variation of ignition time with hot air flow
velocity.

FIG. 5. Ignitable limit curve for a fixed air tem-
perature.

Ignition time (sec) — chart axis

ignitable limit

165 cm/s

$U_e = 135$ cm/s

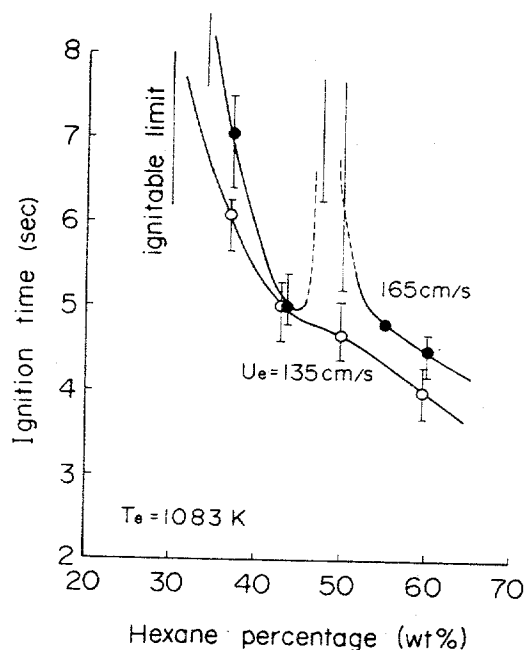$T_e = 1083$ K

Hexane percentage (wt%)

FIG. 6. Variation of ignition time with fuel composition.

Ignition at 135 cm/sec occurs quickly as the hexane percentage increases, with a somewhat long ignition time around 50 wt% of hexane. However, the case of 165 cm/sec is very complex. Between 45 wt% to 50 wt% of hexane, there is either a long ignition time or no ignition beyond the ignitable limit for the lowest concentration of hexane (about 35 wt%). Therefore, three concentration limits for ignition are given when ignition times such as in Fig. 6 are measured between $U_e \approx 160$ to 200 cm/sec (Fig. 5). If we measure ignition times above $U_e =$ 200 cm/sec, ignition will be possible only above 55% hexane.

3.3 Observation of Melting Layer

It is useful to know the condition of the melting region prior to ignition. When the fuel surface is exposed to the hot flow, the gel type condensed fuel begins to melt at the surface and the melting level regresses toward the bottom of the fuel cup parallel to the initial surface. Usually the thickness of the melting layer is about a few millimeters at ignition. Ignition sometimes takes place when the thickness is 5 to 7 millimeters, but there is generally no ignition if the layer formed is more than 5 to 7 millimeters thick. When the layer is thick, bubbles occasionally appear around the melting section. They must be due to so-called micro-explosions caused by heat passing through the brass cup which has a large thermal conductivity. Such micro-explosions, however, are rare and have no relationship to the present characteristic changes in Fig. 5.

A minute amount of carbon powder of several microns was scattered on the initial fuel surface and the movement of the carbon particles after exposure to the hot flow was observed. The carbon particles were seen moving at random in a thin molten layer, and the black particles appeared to gush out from the white melting surface. Also, active movement of particles was observed even after the fuel cup was removed from the hot flow until the layer solidified again, so the shear stress effect due to the external gas flow does not appear to be strong. What effect there is may be caused by the Stefan (bulk) flow due to the phase change from solid to liquid, because a volumetric increase exists in the melting paraffin (about 8 vol.% increase for 50 wt% hexane fuel). The particles, however, move too vigorously for such a small bulk flow. Surface tension may play an important role, but it was not felt necessary to further investigate this flow motion. The main point to be noted is that the melting layer is mixed sufficiently by a comparatively strong and random liquid flow. Therefore, we assume that no distribution of hexane concentration due to a small diffusion coefficient exists in the molten layer.

3.4 Characteristic Ignitability

Several explanations of the ignition behavior described above are possible. First, the phenomenon may be caused by the difference between the initial liquid composition and the gasified fuel composition, based on the liquid-vapor equilibrium rule. The actual measurement of vapor pressure of the mixtures at 333 K does not suggest a complex ignitable limit curve, because the vapor pressure change with fuel composition is almost linear. Since the vapor pressure of paraffin is quite low (3.0×10^{-4} torr at 343 K and 1.31 torr at 473 K), the present fuel is a good approximation of the ideal mixture. Therefore, we must look for other possiblities. The possibility of an extremely slow diffusion (order of 10^{-5} cm^2/sec) of a high volatile fuel (hexane) in the molten liquid layer was dismissed for the following reasons: Provided that there was no liquid flow in the molten layer, a more rapid diffusion in the higher liquid temperature field could be expected, because the gasification temperature increased as the hexane percentage decreased, i.e. ignition should occur easily at lower percentages of hexane. The convection in the melting layer denies this possibility, however. The shear flow effect due to the approaching air flow also made a minor contribution to the present phenomenon, as demonstrated in the preceding section.

A final possibility is, as s... ing paragraph, that a hi... formed in the lower hexa... fuel mixture.

Regardless of how qui... occurs, ignition does not ... the reaction control regio... locity. During this perio... measured by a thermoc... stant temperature close ... lows that steady gasifi... transfer are established ... phase reaction proceed... tense ignition reaction ... observed in the previo... terials.[12] If a certain ... in the melting layer, ... vented the present s... state. As mentioned ... so-called rapid mixi... present melting laye... layer thickness grow... fication period, a co... tained. To be precis... steady state.

Since it is clear f... the quasi-steady va... to ignition, ignitab... dition was exami... steady state inert... centration are sh... specific heat, an... of unity, the ene... tion are easily ... $-\rho u/(2a\rho_e \lambda_e/c$... equal to the ... $(2a\rho_e c_e/\lambda_e)^{1/2}$... thy's conclusio... condition calcu... plicitly obtaini... Clasius-Clape... under the ass... reciprocal of ... ρ, c, λ is de... and thermal ... rection norm... locity in th... nozzle outle... are located ... ature is su... is close to ... abundant ... tration sh... volatile h... ified hexa... and the ... the low... ing poi...

A final possibility is, as suggested in the preceding paragraph, that a higher temperature field formed in the lower hexane fraction of the initial fuel mixture.

Regardless of how quickly sufficient gasification occurs, ignition does not take place immediately in the reaction control region of high external flow velocity. During this period the surface temperature measured by a thermocouple shows a nearly constant temperature close to the boiling point. It follows that steady gasification and heat and mass transfer are established, and that a very slow gas-phase reaction proceeds gradually prior to an intense ignition reaction. This phenomenon was also observed in the previous experiment for plastic materials.[12] If a certain concentration was distributed in the melting layer, slow diffusion of hexane prevented the present system from reaching a steady state. As mentioned in the preceding section, the so-called rapid mixing model is available for the present melting layer. However, since the melting layer thickness grows very slowly during the gasification period, a completely steady state is not attained. To be precise it must be described as a quasi-steady state.

Since it is clear from the above interpretation that the quasi-steady vaporization period is formed prior to ignition, ignitability for the inert gas-phase condition was examined. Examples of the calculated steady state inert profiles of temperature and concentration are shown in Fig. 7. Assuming constant specific heat, and the Lewis and Prandtl number of unity, the energy and species conservation equation are easily solved. The stream function $f = -\rho u/(2a\rho_e \lambda_e/c_e)^{1/2}$, was taken to be approximately equal to the nondimensional distance $\xi = (2a\rho_e c_e/\lambda_e)^{1/2} \int_0^x \rho/\rho_e \cdot dx$. Following Krishnamurthy's conclusions,[14] reasonable accuracy for ignition condition calculations can be expected without explicitly obtaining the solution of the velocity field. Clasius-Clapeyron's equation was also employed under the assumption of the ideal mixture. a is the reciprocal of characteristic flow time (stretch rate); ρ, c, λ is density, specific heat at constant pressure and thermal conductivity, respectively; x is the direction normal to the fuel surface and u is the velocity in the x direction. Subscript e denotes the nozzle outlet condition. Generally, ignition points are located on the air side[11,15] where the temperature is sufficiently high and the fuel-oxygen ratio is close to the stoichiometric ratio. Since oxygen is abundant and fuel is deficient there, fuel concentration should play a more dominant role. If high volatile hexane in the mixed fuel increases, the gasified hexane concentration at the surface increases and the surface temperature decreases because of the low gasification temperature (close to the boiling point). Therefore, a higher fuel concentration
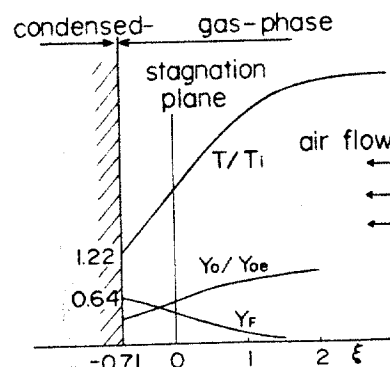
(a). low percentage of hexane (30wt%)
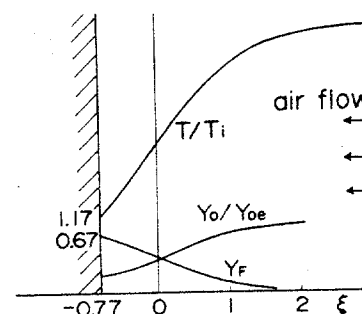
(b) high percentage of hexane (60wt%)

Fig. 7. Examples of calculated temperature and concentration distributions in the quasi-steady state gasification period.

and a lower temperature field form around the ignition point. These contrasting effects of concentration and temperature distribution in the gas-phase mixing layer causes complicated ignitability.

When we intend to analyze the ignition process by means of activation energy asymptotics, distributions of Fig. 7 correspond to the so-called inert-stage solution and can be considered to be the initial conditions for the following transition-stage problem. To know the exact ignition process, the unsteady equation set must of course be solved. However, since the initial reactivity of the field strongly controls the latter process, the best possible description of the characteristic phenomenon observed in this paper is shown in Fig. 7.

4. Conclusion

Ignition tests of mixed fuels (hexane and solid paraffin) exposed to a hot air stream show a characteristic variation with the composition of the fuel.

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As the hexane mass fraction increases, maximum critical velocity for the ignitable limit peaks near 40 wt% of hexane and the minimum occurs around 50 wt%. Therefore, when the hexane mass fraction is changed for a constant flow velocity and temperature, ignition times approach the infinity (at the ignitable limit), and this can happen at three different hexane contents for a certain flow velocity.

Random and active flow motion exists in the molten layer of the mixed fuel and the rapid mixing model is available for the present fuel. Accordingly the steady state gas-phase scheme was analyzed and ignitability was discussed. Such characteristic variations in ignitability are due to two competitive phenomena: (1) the gasified hexane concentration becomes large as the hexane fraction of the condensed mixed fuel increases, and (2) the surface temperature decreases and the whole temperature level in the mixing region of oxygen and gasified fuel drops.

The present ignition characteristic is especially prevalent in combinations of fuels whose boiling points are very different. It also occurs in the ignition of other configurations such as an oil pool, a droplet, a spray and so on, as well as for other ignition sources because the above-mentioned competitive effects are always present.

An unsteady analysis must be conducted for the present problem to confirm the ignition characteristics obtained here. While the present experiment considered only the ignition of binary mixtures, other combustion features of multicomponent fuels, e.g. flame spread, extinction, etc. await further investigation and exact analysis, utilizing activation energy asymptotics.

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